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Energy Dependence of Effective Neutron Absorption Probability of Neutron Absorbing Materials

Junhyun Kwon*, Young-Bum Chun
Materials Safety Technology Development Division, Korea Atomic Energy Research Institute, Daejeon, 34057, KOREA
**Corresponding author: jhkwon@kaeri.re.kr*

1. Introduction

Spent fuel is being generated continuously by the operation of nuclear reactors. It is stored in the spent fuel storage pool for a period of time on site and then may be transferred to a wet or dry storage facility. Neutron absorbing materials are required for interim storage of spent fuel, as well as long-term disposition. In operating the spent fuel facility safely for a long time to prevent criticality, effective neutron absorbers are necessary for a preferred option. The use of neutron absorbing materials is expected to result in a reduction in neutron flux within a system to a level at which neutron-induced chain reactions are not sustainable.

According to the IAEA safety guide [1], it is required that the subcriticality of spent fuel should be maintained under all credible circumstances. Where spent fuel cannot be maintained to be subcritical by geometrical configurations, additional means such as fixed neutron absorbers could be applied. Consideration should be given to qualification and acceptance of neutron absorber materials, including the effects of aging, corrosion, mechanical integrity and handling on the neutron absorbers *etc*.

In this study, we examined the effective neutron absorption probability of various elements from thermal through epithermal neutron energy ranges. Especially, we evaluated the group-averaged neutron absorption cross sections and investigated the resonance integrals. Then, we compared the neutron absorption cross sections for commercial and newly-developed absorber materials.

2. Methods

In this section, the procedure of calculating cross sections for absorbing elements is described, which are obtained from the ENDF/B-VIII library through BNL NNDC site [2]. We examined the values of resonance integral with reference to the JENDL-5 database provided by JAEA NDC site [3]. Among various neutron-absorbing elements, two major elements of our interest are B and Gd, which are constituents of the neutron absorbing materials. Besides two absorbing elements, we investigated other ones such as Hf, Sm and In, as well as alloying chemicals. Table I shows the chemical compositions and weight fraction of three neutron absorbing elements; commercial borated-stainless steel (SS) and Boral®, and a developed Ti-based alloy containing Gd, named as KONAS 163.

Table I: Chemical compositions and weight fraction of neutron absorbing materials

Materials	Elements (w/o)										
	B	C	Al	Si	Ti	Cr	Mn	Fe	Ni	Mo	Gd
Borated-SS	1.7	0.02	-	0.2	-	18	1	66.8	12	-	-
Boral®	30.8	8.5	60.7	-	-	-	-	-	-	-	-
KONAS 163	-	-	-	-	91.7	-	-	1.67	-	1.91	4.71

2.1 Calculation of Group-Averaged Cross Sections

Generally, neutrons in a thermal reactor have energies ranging from 10 MeV down to below 0.01 eV – nine orders of magnitude. We divide the whole energy range into 20 groups between 0.001 eV and 10 MeV for convenience sake. Because the neutron spectrum for the spent fuel storage is not available, collapsing the cross section over the spectrum is not possible. We calculated the group-averaged value using the FORTRAN program.

The cross section data for target elements were collected from the ENDF/B-VIII library [2]. Because the library does not provide the absorption cross section in one file, we collected both total and elastic scattering cross sections and then processed to calculate the group averaged-value. Fig. 1 shows total and elastic scattering cross sections for Gd-157, where solid curves are from the ENDF/B library and the dotted step lines represent group-averaged values. For all natural isotopes listed in Table I, we calculated the group-averaged cross sections.

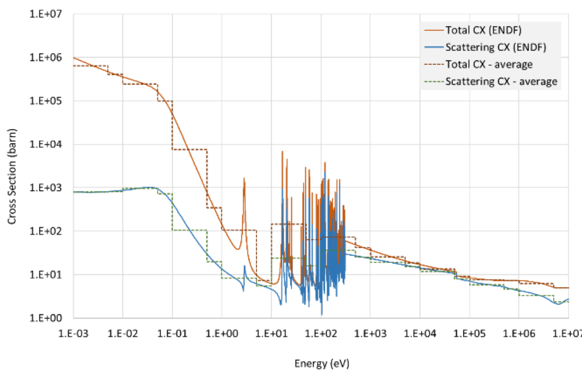

Fig. 1. Total and elastic scattering cross sections for ^{157}Gd (curve: ENDF/BI, dotted-step: group-average)

2.2 Average Cross Sections in Epithermal Energy

The cross section is a function of the incident neutron energy. Although the cross section is a continuous function, the function behaves in a differently for thermal and epithermal neutrons. While the log-log plot of cross section vs. neutron energy is linear for thermal neutrons as shown in Fig. 1, the cross section becomes unpredictable in epithermal range. The average behavior in the resonance region is very difficult to describe. In order to characterize the average cross section of resonance regions, the resonance integral is estimated assuming that the flux behaves as the inverse of neutron energy. The JAEA NDC site provides the resonance integral values for specific nuclear reactions of elements, which were derived using the following equation [3]. We simply put together all tabulated values and use them to compare the effective absorption probability in the epithermal neutron energy range between E_L = 0.5 eV and E_U = 10 MeV.

$$\sigma_{RI}(T) = \int_{E_L}^{E_U} \sigma(E,T) \cdot \frac{1}{E}\, dE \qquad (1)$$

3. Results

The absorption cross section (σ_{abs}) for each isotope was calculated from the difference between total (σ_t) and elastic scattering cross section (σ_{el}), which is given by:

$$\sigma_{abs} = \sigma_t - \sigma_{el} \qquad (2)$$

Considering the natural abundance of the isotopes, we can generate the absorption cross sections for neutron absorbing elements, which are shown in Fig. 2. Also, the resonance integral values for each element are listed in Table II.

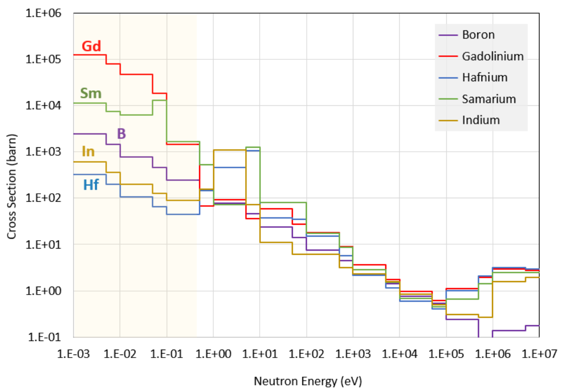

Fig. 2. Absorption cross sections for neutron absorbing elements including B, Gd, Hf, Sm and In

Table II: Resonance integral for neutron absorbing elements

Element	B	In	Sm	Gd	Hf
σ_{RI} (barn)	342	3085.6	1440	404	1977.3

The group-average thermal cross section (0.01-0.05 eV) and resonance integral for alloying elements are listed in Table III. For three absorbing materials listed in Table I, the absorption cross sections are plotted in Fig. 3 where their resonance integrals are included. While the Ti-based model alloy shows the highest absorption cross section for thermal neutrons, its resonance integral is lowest in the epithermal range.

Table III: Thermal cross section and resonance integral for alloying elements (unit: barn)

Elements	Al	Ti	Cr	Mn	Fe	Ni	Mo
σ_{th}	0.23	6.45	3.11	13.4	2.6	4.1	2.5
σ_{RI}	0.12	1.94	1.55	13.5	1.4	2.65	23.1

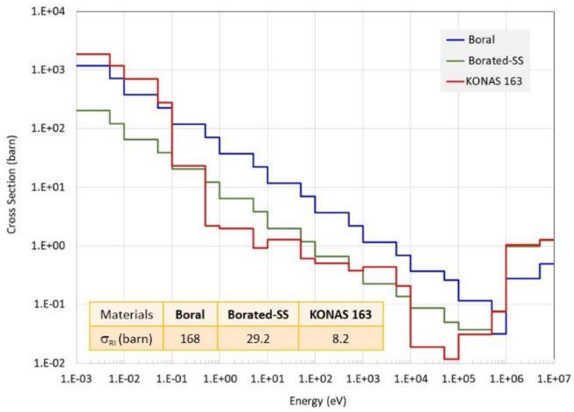

Fig. 3. Absorption cross sections and resonance integral values for neutron absorbing materials of Boral, borate-SS and Ti-based model alloy

4. Discussion

For criticality control of spent nuclear fuel in storage and transportation, the most commonly used neutron absorber materials are B-containing ones. While B has a number of advantages in terms of availability and economics, its addition to metal is limited due to low solubility. In neutron absorbing materials, the continued presence and effectiveness of the absorbers are important. In this study, we examine the neutron energy dependence of absorption cross sections for various elements and investigate the absorption capability of our developed Gd-containing alloys. Whereas new alloys exhibit the higher absorption probability in thermal neutron, the lower absorption probability is shown in the epithermal range.

REFERENCES

[1] IAEA, Storage of spent nuclear fuel, IAEA Safety Standards No. SSG-15, 2012.
[2] Evaluated Nuclear Data File (ENDF)/B-VIII, http://www.nndc.bnl.gov/, Brookhaven National Laboratory, US.
[3] Japanese Evaluated Nuclear Data Library (JENDL), http://wwwndc.jaea.go.jp/, Japan Atomic Energy Agency, Japan.